High Resolution Soft X-Ray Spectroscopy for Constellation X

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ABSTRACT

The Constellation-X mission, with 5 to 10 times the collecting area of any previous x-ray observatory, will obtain high-throughput, high resolution spectroscopic observations of x-ray sources ranging from super-massive black holes to the disks around young stars in the 0.25-4.0 keV region of the spectrum. We describe the need for high resolution X-ray spectroscopy on the Constellation-X mission, the various options for obtaining it, and the implementation that we recommend;, e.g. an off-plane grating system that can simultaneously provide spectral resolutions ($\lambda/\delta\lambda$) as high as 3000 and substantially increased throughput in the 0.2 to 2.0 keV region.

As a flagship mission, Constellation-X will be a general purpose facility for the astronomy community. The reflection grating system we describe will enable Constellation-X to address the important questions of the next generation within NASA's current cost target.

Keywords: spectroscopy, X-ray, observatory, astronomy, high-resolution, reflection grating, off-plane

1. INTRODUCTION

Since its inception just a few brief years after the start of the space age, X-ray Astronomy has grown to takes its place as a fundamental pedestal in our understanding of the universe. Largely because of X-ray Astronomy, Black Holes are now generally recognized as a common component of the universe, one that has played a central role in the very structure of the Universe around us. With Chandra, x-rays took their place alongside visible light and the Hubble Space Telescope in imaging the sky. The x-ray spectrum is dense with atomic transitions, exceeding even the ultraviolet in its diagnostic power. Chandra opened the field of x-ray spectroscopy, but it has barely scratched the surface.

Constellation-X is generally recognized by the US x-ray community as the necessary next step in the evolution of the field. A major increase in both spectral resolution and collecting area is needed to move the field forward, allowing it to address new, fundamental questions such as the nature and behavior of matter just above event horizons. Con-X is designed to provide that leap in capability, giving NASA a new window on the physical processes at work in the Universe.

Constellation-X will increase the collecting area of x-ray observatories by over an order of magnitude compared to the current state of the art. Its spectral resolution must similarly rise to enable fundamental plasma diagnostics like absorption lines and Doppler shifts to be obtained. Indeed, in the fall of 2006, the Constellation-X Project underwent an intense review of spectral resolution requirements. It reaffirmed the need for $R=E/\delta E\sim3000$ for the best diagnostics at the Fe K complex. It went on to raise the required resolution below 1keV from $\lambda/\delta\lambda\sim300$, where it had been set before the launch of Chandra, to $\lambda/\delta\lambda\sim1250$ with a goal of 3000.

Consider the spectroscopic data obtained by the OAO-2 and OAO-3 missions. OAO-2 obtained low resolution spectroscopic data for ultraviolet stars which is largely forgotten today. OAO-3 obtained high resolution spectra, was renamed Copernicus, and revolutionized our understanding of the interstellar medium. Also consider that Chandra was launched in 1999 with 30 cm^2 of collecting area and a resolution of 500 to 1000, while XMM/Newton launched the following year with six times the collecting area and about one third the resolution. The results from Chandra have largely eclipsed the results from XMM. History argues that in the real world, beyond simulations, high resolution is more important than high throughput.

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However, there are a limited number of techniques that will support the high resolution needed for Constellation-X, since the Soft X-ray Telescopes may provide only 15 arc seconds of spatial resolution. Reflection gratings in the extreme off-plane mount appear to offer the best approach.

In this paper we first revisit the science behind the drive for high resolution. We then review the various approaches to spectrograph design within the constraints of Con-X. We show how the off-plane grating can provide the needed capability. We then describe our conceptual design for a full scale prototype grating array suitable for test in the converging beam of the XMM flight spare mirror at the Panter facility. Our goal is very simple. We wish to take the off-plane grating spectrograph to an unquestioned Technology Readiness Level-6.

This demonstration will show the feasibility of such devices for future X-ray missions such as Constellation-X. Our plan is to perform a design study to validate the geometry required of the thin flat gratings to meet the minimum optical performance requirements, including the selection of the substrate material. Two opposing portions of a grating assembly will then be designed, fabricated, and assembled, and tested in an X-ray beam to demonstrate the performance properties of off-plane gratings. The test data will be analyzed to show the performance of a full flight system, including optical and environmental performance

2. THE SCIENCE CASE FOR HIGH RESOLUTION SPECTROSCOPY

The following section presents three examples of why high resolution is crucial to the success of Constellation-X:

A. AGNs

The X-ray spectra of Active Galactic Nuclei (AGN) show blue shifted absorption lines which are interpreted as outflows. In recent years, the potential impact of these outflows on their environment has become widely recognized, including their effects on: the growth of super-massive black holes[1,2,3], evolution of the host galaxy[4,5,6,7], enrichment of the IGM[8,9], entropy of the IGM[10,11], cluster cooling flows[12,13,14,15,16], magnetization of cluster and galactic gas[9], and the luminosity function of quasars[17]. Thus both Chandra and XMM-Newton have allocated several million seconds of observing time to studying AGN outflows. Their observations show the need for X-ray telescopes with considerably higher spectral resolution.

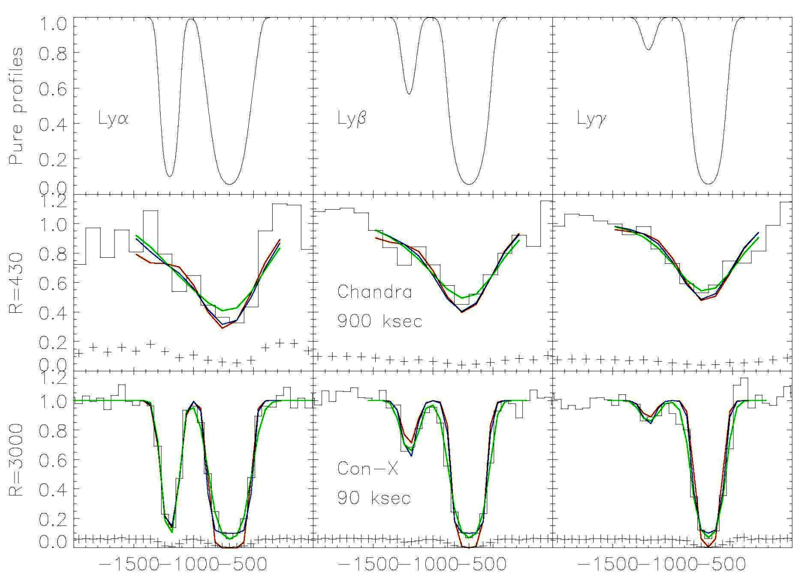

Fig 1: Simulated data of two-component C(v) absorption profiles are fit with full covering (red), C=0.9 (dark blue), and two-component C(v) (green). Pure absorption profiles are shown on top, MEG simulation in the middle, and Con-X simulation below. Lyman-α through -γ are plotted from left to right, and plus signs show error.

A conclusive study of AGN outflows rests upon the determination of accurate ionic column densities (N_{ion}) from absorption lines of a large number of elements, several ionic species per element, and when possible, more than one transition per ion. With photo ionization models these column densities can then be used to infer the physical conditions of the absorbing gas: ionization equilibrium, total out flowing column density N_H, temperature and elemental abundances. These quantities in turn yield the ultimate goal for AGN studies: the mass flux and kinetic luminosity of the outflows

By analyzing high quality UV data of AGN outflow lines it has been shown that traditional absorption measuring techniques (equivalent width, apparent optical depth, and Gaussian modeling) yield highly inaccurate N_{ion} determinations[18, 19, 20, 21, 22]. This occurs because the shape of outflow lines is not solely dependent on optical depth. Instead, a convolution of velocity-dependent optical-depth and covering-factors are responsible for the line shapes. Similar results were obtained for the flagship of warm absorber data sets: the Chandra 900 kilo second observations of NGC 3783 [23].

Therefore, covering factor analysis is the only way to extract the science from spectral data of AGN outflows. For such an analysis we need high S/N data, but even more importantly, high spectral resolution. There is no way to separate covering fraction from optical depth without high spectral resolution. The simulation in Figure 1 shows the crucial difference between a Chandra-like resolution of R=430 and R=3000.

We have generated synthetic spectra that are similar to the Lyman series observed with the Chandra MEG grating. We did this for both the characteristic of the Chandra MEG grating (R=430) and an assumed Con-X grating with R=3000 and an effective area of 3000 cm^2. To demonstrate the difference between the resolution of the two instruments, we fit the synthetic data (upper panels) with three covering factor models: full covering, a constant partial covering C=0.9, and the velocity dependent covering fraction C (v) that was used to create the synthetic data. The middle panel in Figure 1 shows these fits to the MEG synthetic data. It is obvious that the three fits are indistinguishable. Formally, the χ^2_{red} for C=1, C=0.9, and C (v) are 1.23, 1.19, and 1.2, respectively. The MEG resolution impairs our ability to distinguish between the models. By comparison, the bottom panels with Con-X synthetic data demonstrate a clear distinction. The χ^2_{red} for C=1, C=0.8, and C (v) are 22.9, 6.2, and 1.1. This clear distinction between the different models allows us to extract the science from the data, which is not feasible with the R=430 data.

It should be noted that the complexity now seen in the AGN spectra will also extend to the iron K lines at 6 keV. Can the iron lines that are so crucial to the principal science goal of Con-X be properly interpreted without a complete analysis of the system?

B. WHIM

The location of the "missing baryons" in the Warm-Hot Inter-galactic Medium (WHIM) is a major astronomical puzzle. Where is the 90% of ordinary matter not contained in luminous, collapsed form (galaxies, groups, and clusters)? At high red shift much of this matter resides in the intergalactic medium (IGM). Does intergalactic space provide a similar gaseous reservoir at low redshift (z<0.5)? If so, what are the implications of this gas for late-time infall onto galaxies and for the chemical evolution of their disks and halos?

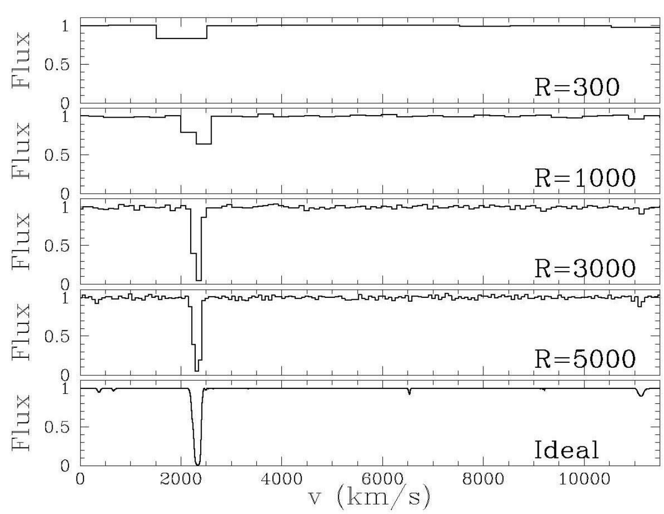

Fig. 2: Simulation of the O VIII Lyman-α line at 20.02Å in the direction of PKS 2155-304. Line saturation is evident for resolutions greater than 3000. At lower resolution one would likely conclude that the line is optically thin.

Theoretical simulations[24, 25] of large-scale structure and cosmological hydrodynamics suggest that the IGM is a hierarchically structured, filamentary network (the "cosmic web") shaped by the processes of gravitational collapse, shock-heating from galactic outflows, and photo-ionization by QSOs. The cosmic web therefore provides a rare opportunity to observe cosmological processes at work: the gravitational instability of dark matter; baryonic infall and shocks; and radiative, mechanical, and chemical feedback from galaxy formation.

We need an improved spectroscopic capability to revolutionize X-ray IGM science. Astronomers need to probe numerous AGN sightlines in a census of "missing baryons" in the WHIM using X-ray absorption lines of O VII, O VIII, N VI, N VII, C VI, Ne IX, etc. [26, 27].

Detecting and measuring the Cosmic Web is a worthy challenge, requiring high-throughput spectrometers aboard X-ray and ultraviolet telescopes. The warm phase (10^4 K) of the IGM has been detected by the HST Lyman-alpha survey[28].

Approximately 30% (+/- 4%) of the baryons reside in this photo-ionized gas and another 5-10% is in collapsed halos.

Approximately 5-10% has been inferred from UV resonance lines of O VI, a sensitive tracer of gas at 10^5 - 10^6 K[29]. This leaves 40-50% unaccounted for, perhaps residing in the theoretically predicted gas at T > 10^6 K. These baryons are only detectable in X-ray absorption from high ions of trace heavy elements.

In view of the potentially larger baryon reservoir in the hot IGM, X-ray spectroscopy of the WHIM should be brought up to at least the current level of O VI spectroscopy with FUSE. Detections of weak O VII and other X-ray absorbers can be achieved, both by increasing A_{eff} to at least 2,000 cm^2 (at 0.3-1.0 keV if R = 1500) and by obtaining a better match between the velocity (FWHM) resolution element ($\delta V = c/R$) and the expected equivalent widths (W_v) and thermal line widths of the WHIM absorbers. The minimum detectable column density of a given ion scales as:

$$N_{min} \sim (\text{line strength})(\delta V)_{FWHM} / (S/N)$$

where the intrinsic line strength is given by the product, ($f\lambda$), of oscillator strength and wavelength. The velocity resolution and signal-to-noise ratio (S/N) are determined by the properties of the instrument and the duration of the observation. For fixed A_{eff}, the (S/N) is proportional to $(A_{eff})^{1/2}$, so N_{min} scales as the square root of the resolution element, $(\delta V)^{1/2}$. For this reason, it will be important to understand the instrumental and cost trade-offs between effective area and resolution.

Typical X-ray absorption lines (O VII, O VIII) are intrinsically 10-40 times weaker than their UV counterparts (O VI, Ne VIII). As a result, current UV spectrographs with 10-20 km/s resolution (HST/STIS and FUSE) can detect O VI (1032 Å) down to column densities N (O VI) $=10^{13} cm^{-2}$, while the claimed Chandra detections of the WHIM have N (O VII) $=10^{15}$ cm^{-2}, a factor of 100 difference.

Thus, one can justify resolutions ranging from R = 1500 for IGM absorber-galaxy kinematics up to R=5000 for line profile studies. Con-X should provide sufficient line sensitivity and separability to resolve the expected dynamic structures in the WHIM. These capabilities would allow Con-X spectra to be tied to the current moderate-resolution UV spectra (HST, FUSE) of H I, O VI, C II, C IV, and other metal ions. These capabilities would then allow astronomers to use Con-X as a powerful tool for studies of the missing baryons and large-scale structure in the hot, shocked IGM.

However, the potential rewards of this program are great, particularly when the X-ray diagnostics of the hottest WHIM plasma are combined with similarly increased capability for UV spectroscopy in lines of H I, O VI, C III, C IV, etc. The proposed Con-X mission could therefore do this science, and a XEUS mission with A_{eff} = 40,000 cm^2 and R = 5000 might be possible. This increase in capability would enable a major study of the WHIM.

C. Stars

Our first two examples of the need for high resolution spectroscopy feature absorption lines. Emission line spectroscopy has a different set of requirements, but we show that the need for high resolution remains.

Emission line objects are well represented by stellar coronae because they exhibit the full range of thin plasma diagnostics. Included in the purposes of studying stellar x-ray spectra are temperature structure, density, and outflow wind velocities. In Figure 3 we show a simulated part of the spectrum of σ^2 CrB, an

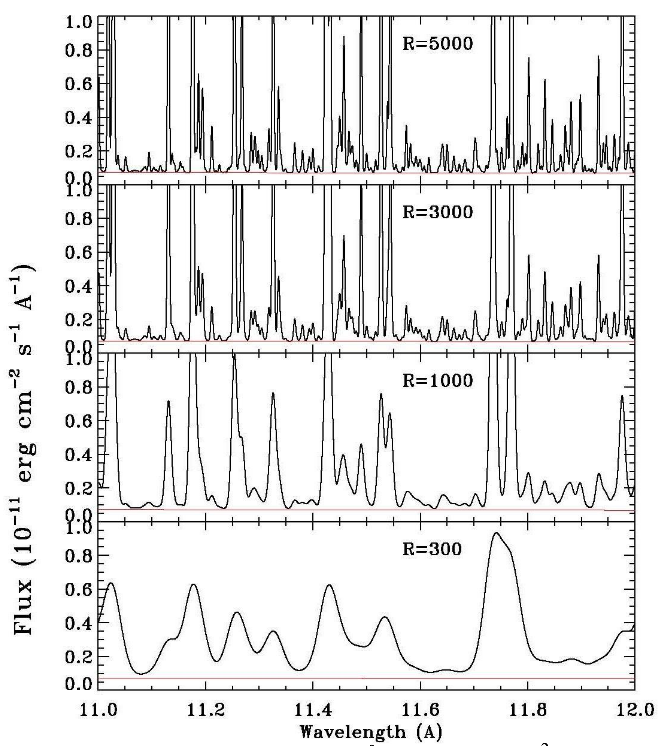

Fig. 3: Simulation of the 11-12Å spectrum of σ^2CrB at different resolutions. The horizontal line just above zero flux is the computed continuum. At a resolution of 1000 it is difficult to measure the continuum flux even with very high S/N. An accurate continuum measurement is essential for determining metal abundances relative to hydrogen.

X-ray active spectroscopic binary. A study of this figure shows a large part of the story. At resolutions below 1000, one can see the existence of the strongest lines, but plasma diagnostics are impossible. Above 1000, one can measure the continuum and the strength of isolated lines. To properly resolve diagnostic lines a resolution closer to 3000 is needed. To measure line width and find line asymmetries requires a resolution of at least 3000.

Only Constellation-X will have enough collecting area to service the resolution required to obtain the crucial diagnostics that will reveal the basic physics of emission line regions. Stellar x-ray spectroscopists need this high resolution and hope the next x-ray astronomy facility should not fail them.

3. DISPERSIVE OPTIONS FOR HIGH RESOLUTION SPECTROSCOPY

Non-dispersive spectroscopy is superior to dispersive spectroscopy because it has higher efficiency and lower internal background. However, in some critical bands of the spectrum, calorimeters and other non-dispersive instruments have not yet shown an ability to reach the spectral resolution needed for Constellation-X. For example, achieving a resolution of 3000 at 0.3keV would require an order of magnitude improvement in energy resolution, and major advances in window and refrigerator technology. Bragg crystals are much too inefficient, so gratings remain the only demonstrated path to the required performance.

A. Comparison

Diffraction gratings come in three varieties for the purposes of x-ray astronomy: transmission gratings, in-plane reflection gratings, and off-plane reflection gratings.

1. Resolution

For all diffraction gratings the equation for resolution is given by

$$R = \frac{\lambda}{\delta\lambda} = \frac{E}{\delta E} = \frac{\sin\gamma(\sin\alpha + \sin\beta)}{B\cos\alpha}$$

as defined in Cash (1982)[31]. In particular, B is the resolution of the telescope beam in radians. For transmission gratings this equation reduces to

$$R = \frac{\sin\beta}{B} = \frac{\lambda}{dB}$$

where d is the groove spacing. Con-X has a telescope with 15 arc second resolution, so B is $7.5\text{x}10^{-5}$. Currently the highest groove density contemplated is about 10,000 g/mm so *d* can be no lower than 100nm. At 1keV, λ = 1.24 nm. So R will be, at most, 166. For in-plane gratings the equation simplifies to

$$R = \frac{(\alpha' + \beta')}{2\alpha'}\frac{(\alpha' - \beta')}{B}$$

where α' and β' are the complements of the usual α and β, making them small angles near the graze angle. In a typical in-plane design, $\beta \sim 2\alpha$ and $\alpha \sim \theta/2$ where θ is the graze angle. So we find $R = 3\theta/4B$. Using θ = 2.7 deg we find that in-plane gratings will be able to achieve a resolution of 470. For off-plane gratings γ is about equal to θ, so

$$R = \frac{\theta}{B}\frac{(\sin\alpha + \sin\beta)}{\cos\alpha}$$ which reduces to $$R = \frac{2\theta\tan\alpha}{B}$$ in the efficient Littrow mode.

Using a blaze angle of 30 degrees we find that the off-plane resolution is 725. By pushing to a high blaze such as α = 63 degrees, the resolution rises to 2500.

Subaperturing. Subaperturing is the technique of using the anisotropic blur function of grazing incidence telescopes to substantially improve resolution. Cash[32, 33] and McEntaffer, et. al.[34] have shown that subaperturing could be used to raise the resolution of the Con-X RGS to 3000 or higher and still maintain good throughput. None of the resolution numbers above is high enough to justify using it on Con-X, however, except for the off-plane echelle with α = 63. There are potential difficulties with fabricating such high blaze gratings, so the approach should be studied, but not relied upon at this point.

In principle, subaperturing has the potential to raise the resolution by a factor of 2.5f, where f is the focal ratio of the telescope. Con-X is an f/6, so a factor of 15 is potentially available. It is theoretically possible to achieve R=725x15= 10,400 with a 30 degree blaze grating and R=2500 x 15 = 37,500 with an echelle grating. In practice the resolution will be limited by considerations of fabrication, tolerance and efficiency well before this level is achieved.

2. Efficiency

Each of the three approaches has efficiency considerations: Transmission gratings are, by their very nature, blazed for zero order. Furthermore, half the light is blocked by the bars that do the diffracting. The gratings on Chandra exhibit efficiencies near 6 %, and future improvements might reach as high as 10 %.

In-plane gratings have groove shadowing that limits their efficiency to about half the reflectivity. Typical in-plane gratings achieve 24 % efficiency in first order and 4 % in second order. Off-plane gratings can achieve full groove illumination and thereby approach efficiency equal to the grating reflectivity. In practice 38 % efficiency is common.

3. Mechanical Considerations

There are a variety of other effects that need to be mentioned.

Tolerances: In-plane reflection gratings have the tightest flatness tolerances because they disperse the light in the same direction as the bulk of the errors go. Transmission gratings have very forgiving flatness tolerances because they transmit instead of reflecting the light. Off-plane gratings have significantly looser flatness and alignment tolerances because these errors cause astigmatism, rather than loss of resolution.

Fabrication of Gratings: Transmission gratings are free-standing cobwebs and can be very difficult to fabricate. On the other hand, because they operate at normal incidence, a much lower area is needed. Replication is impossible. In-plane gratings require lower groove density than do the off-plane gratings, but they have to be blazed at a very low angle. Maintaining the groove flatness turns out to be more difficult than making higher density gratings with high blaze angle.

Mass: Transmission gratings appear to have a major advantage in being thin and light. However, when one adds in the mass of the structure the advantage is not so large. When convolved with the lack of efficiency, one finds that reflection gratings give more signal per unit mass.

Packaging: Transmission gratings pack into a plane and can be easily removed from the beam as is done with Chandra. Off-plane gratings have a substantial advantage over in-plane gratings. Because in-plane gratings disperse upward, away from zero order, the gratings must be widely spaced to avoid vignetting. Typically, half the beam passes through unused. Off-plane gratings diffract parallel to the plane of the grating and thereby can be as densely packed as needed.

4. Comparison

In our judgment transmission gratings will not generate enough resolution to be of value to Con-X, and in the comparison between in-plane and off-plane reflection gratings, the off-plane gratings win by a substantial margin in all categories.

B. Off-plane Grating Geometries

In the preceding section we showed that, based on fundamental principles, off-plane gratings give superior performance in nearly all applications. However, can they deliver the needed performance within the tight constraints of Con-X? The answer appears to be "yes", but it will take some serious study to prove it. An off-plane grating array fits easily into the fiscal and spatial envelopes. The mass constraint merits the most study.

The Constellation-X project has supported serious study of off-plane grating geometries at the University of Colorado. Those studies demonstrated that off-plane gratings greatly outperform in-plane gratings.[31-47] Off-plane gratings can simultaneously provide resolution as high as 3000 ($\lambda/\delta\lambda$) and throughput that exceeds minimum requirements.

However, the grating arrays envisioned and studied to this point cannot fit within a 100 kg mass limit. Those RGS's consisted of approximately 240 grating modules, each containing a score of off-plane gratings. Each module created about 12 cm^2 of effective area to generate the spectrum for a total of about 3000 cm^2 as originally required by Con-X. In that architecture each of the four Soft X-ray Telescopes had its own grating array and a CCD array in the focal plane.

1. Reduced Throughput RGS:

The simplest solution to the mass problem is to reduce the number of gratings. If we were to place 40 modules on only one SXT, with only one CCD array, the RGS mass would be down around 100 kg. Such a device would have resolution in excess of 3000 and collecting area in the vicinity of 500 cm^2. As such, it would exhibit nearly an order of magnitude improvement in resolution and throughput over Chandra. It would provide a unique capability and help Con-X achieve its goals.

2. Grating Array Closer to Focal Plane:

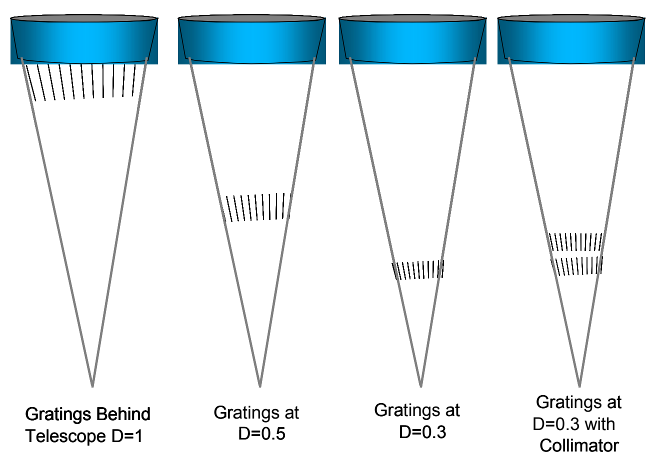

Fig. 4. Grating Locations in the Converging X-ray Beam

An alternative to simply yielding collecting area is to move the gratings closer to the focal plane. Let D be the distance from the focal plane to the gratings, divided by the distance from the focal plane to the telescope. The resolution of the grating array scales approximately as D, because the system is dispersion limited (not aberration limited). The size scale also drops as D, indicating that the mass of the array drops at least as D^3.

Similarly the length of the needed CCD array drops as D, saving more mass and power.

Consider moving the grating array halfway down the converging beam, as shown in Figure 4. The array will now have one eighth the mass and still generate resolution of 1500. At D=1/3 the array is reduced in mass by a factor of twenty seven and the resolution is still above 1000.

3. Full Coverage

Once the gratings have been dropped in size by such large factors, full coverage of the beams should be considered. Most of the high resolution observations needed by the community do not require simultaneous operation at 6 keV and 0.6 keV. One can imagine grating arrays that are inserted into the beam and then removed as needed. This would allow the gratings to utilize the entire SXT collecting area. Effective areas of 10,000 cm^2 or more might be realized in concert with a resolution well above 1000.

4. Extended Sources

For Constellation-X to be a full service observatory, it should be able to perform high resolution spectroscopy on extended sources as well as point sources. In particular, it is likely that higher resolution will be required on clusters of galaxies in the next generation X-ray observatory. Objective grating systems lose resolution rapidly as the size of the object becomes comparable to, or larger than, the telescope resolution. This can be addressed by the use of a special wire grid collimator. A collimator tuned to the convergence of the telescope beam, slid into the beam upstream of the gratings can create a slit-like limitation on the signal reaching the focal plane. Such a collimator has been built at the University of Colorado and was flown on a sounding rocket on November 20, 2006. The performance of such a device needs to be studied in detail.

C. Grating Arrays

The motorized hinge mechanisms used to rotate the transmission gratings on Chandra into and out of the X-ray beam could readily be modified for the Constellation-X mission.

Our design concept for a four-SXT Constellation-X spacecraft is shown in Figure 5. The collimator and off-plane reflective grating modules described in the previous sections are located approximately 3 meters from the X-ray focal plane. Boxes for the detector and mechanism drive electronics are also shown. When not in use, the collimator/grating modules are rotated out of the beam with their hinge mechanisms. Each beam has an array of CCD's positioned around it as shown in Figure 6.

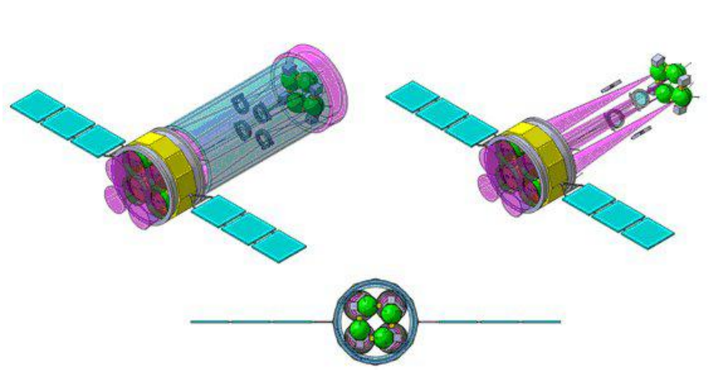

Fig. 5: Conceptual design of a four Soft X-ray Telescope version of Constellation-X. The collimator/grating modules are rotated in and out of the x-ray beam with mechanisms derived from Chandra. The dewars for the micro-calorimeter instruments and the spectrometer detector electronics are also shown.

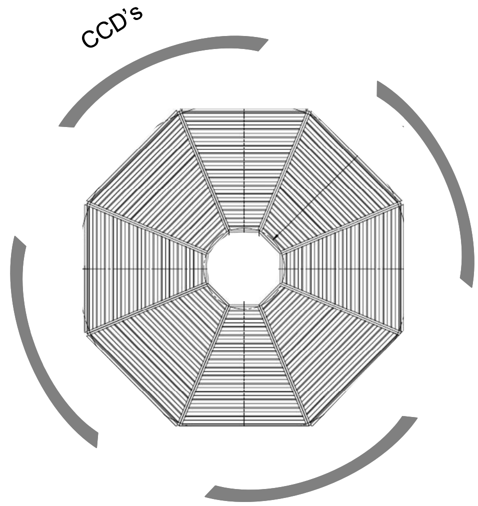

Fig. 6: The grating array could be divided into octants, feeding four CCD arrays.

4. GRATING DEVELOPMENT

Our primary goal is to show that a grating design that uses thin, flat gratings can meet the currently envisioned mission goals for Constellation-X in terms of optical quality, spectral resolution, and efficiency; can be packaged into a mechanical unit; and can survive the launch environment. Previous work by the University of Colorado and others has determined the required angle of incidence and has parameterized the properties of the grating substrate material. Our challenge is to generate an opto-mechanical design for such a unit.

The first step will be to model the grating assembly for Con-X with full, efficiency-enabled ray tracing with tolerances. This will allow us to create an optical design that will achieve a resolution of at least 1500 and identify possible paths to our goal of R=3000. We can then start procurement of the grating master. We also plan to take a radial grating we already have on hand to Panter to perform experiments with high resolution spectroscopy in the converging beam of the XMM flight spare with cooperation of our colleagues at MPE. The XMM flight spare is the one telescope that, in whole world, best approximates the expected performance of the Con-X Soft X-ray Telescopes (SXT)s.

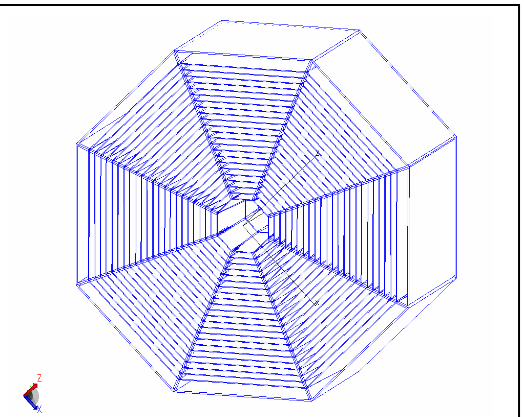

Fig. 7: Our design concept for the full grating array unit that will be inserted into the beam. The unit thickness is approximately 8 inches, and the entire array is approximately 18 inches in diameter.

As part of the design effort, we will perform a trade study to validate the replica grating process on these thin substrates that will minimize the thickness of the substrates, thus improving transmission efficiency while not sacrificing optical quality, which would negatively impact the performance of the spectrometer.

(1). Spectrometer / Grating Unit Preliminary Design

We plan to build the core portion of a grating assembly that could be used in a space-based X-ray telescope such as the one proposed Constellation-X mission. We have developed a baseline concept, shown in Figure 7, which would be placed in the converging X-ray beam of the telescope approximately 3 meters from the detector array.

Figure 8 shows a CAD drawing of a single "pie slice" of the design as we currently envision it. A preliminary mass estimate for the unit, assuming it is made entirely out of Beryllium S-220F, is 28.4 kg; which includes a 25% contingency factor given the immaturity of the design.

The design activity will determine how many of the gratings in the array will need to be installed to have a meaningful test, and what the arrangement of those gratings should be. We tentatively plan to install a few gratings in each of two opposing pie slices, with a simple structure designed to hold them in the proper orientation when it is placed in the test facility beam. The analysis will be performed to show that there is a path from this design to a flight design, and that such a flight design will survive the thermal and dynamic environments it will be exposed to. This design will be compatible with a space mission's requirements in terms of assembly procedures and materials, unless the study shows that the required materials do not fit the proposed budgets.

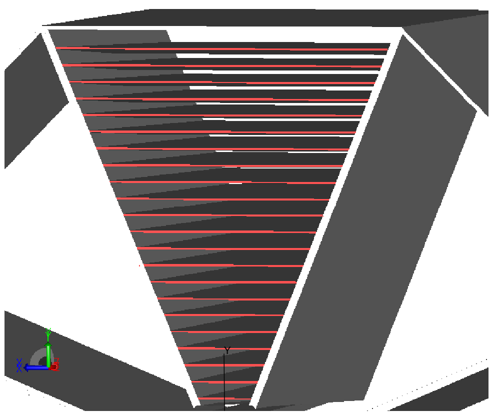

Fig. 8: Solid view of Grating Array with front edge of each Grating highlighted. The gratings range from 1 to 7.8 inches wide by approximately 8 inches in depth.

The grating assembly design effort includes the following sub- tasks:

- Finalize all requirements, including optical quality for gratings (to use for sample evaluation in above task)
- Develop preliminary drawings for the delivered item and concepts for a "flight" configuration
- Verify the preliminary optical design can be manufactured to the required mechanical tolerances
- Perform preliminary optical analysis to determine number of gratings and placement of gratings required for test configuration to obtain meaningful results
- Include mechanical features that will allow integration and alignment of the unit into the X-ray test facility
- Take the design to a PDR level and hold a formal review with the team

(2). Grating Substrate Material Properties Trade Study

To achieve a preliminary design that can be manufactured, the material properties of the grating substrates must be demonstrated. The gratings themselves will be replicated on a substrate material which is in a trapezoidal shape to permit light to pass through the array of gratings at a grazing incidence as shown in Figure 9.

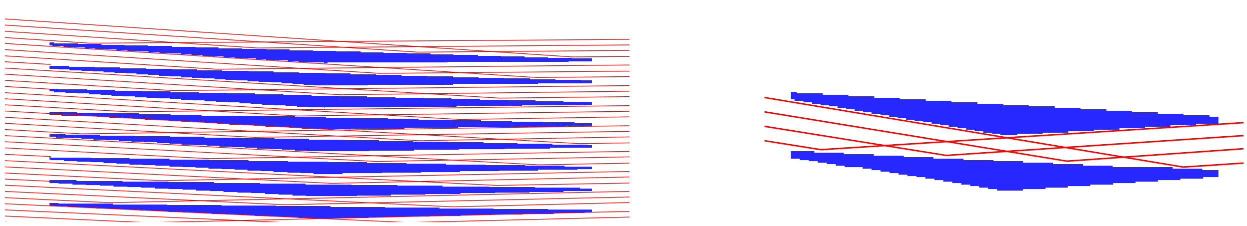

Fig. 9: The figure on the left shows the x-rays coming through the front of the grating array and the figure on the right shows two gratings with the cross-sectional dimension exaggerated to show how the rays reflect off of the flat grating surface and continue down the optical path. The trapezoidal shape is required to minimize shadowing of the incoming beam. The angle of the trapezoid is about 2 degrees.

Our current design requires an edge thickness for the substrate material of ~1 mm. To achieve the optical quality at this thickness, the material must be very stiff, since the grating replication process will produce a "bi-metallic" effect which can distort the substrate, particularly when the grating is thermally cycled. The edge thickness is a parameter in the trade space along with the material selection. As part of our material trade study, we will procure a few substrate samples and have a representative grating replicated to validate both the replication process and to show that such thin substrates can be used for grating replication without significantly degrading the optical quality.

On the basis of our preliminary analysis, we plan to procure a few beryllium (Be) substrates of the largest size needed for the unit, and to test the replication process on substrates with different thickness. The final substrate sample thicknesses will be determined by reviewing earlier test articles and material selections and their results, along with mechanical analyses of Be and potential alternative substrates such as silicon carbide (SiC). There is an option to test SiC or other material samples instead of Be samples if the analysis shows any risks or benefits to either material or vendor ROMs are not cost prohibitive.

The test article will have the requisite number of gratings substrates and a test frame fabricated from beryllium to make it as flight-like as possible and ensure alignment is stable over all operating temperatures. The number of gratings replicated will be determined by funds available and the optical analysis performed in the preliminary design phase. There are 22 gratings in each pie slice and we currently plan to populate no more than that number total in the two opposing segments. The finish of the grating substrates and the replication process itself are significant cost drivers, as well as the time required to align the gratings. The remainder of the grating locations can be populated with mass simulators to demonstrate the grating transmission factor and the mechanical fidelity of the final system. After assembly and alignment the test article will be thermal cycled to stabilize the gratings and grating simulators in the populated portion of the assembly.

The optical testing will most likely be performed at the Panter facility using the XMM flight spares if the appropriate international arrangements can be made. Performing the tests at the XRCF is also a possibility. The test consists of inserting the grating array into the converging beam of a telescope at the end of a long vacuum beamline and calibrating it.

5. SUMMARY

Off-plane reflection gratings can provide a high resolution spectroscopic capability for future X-ray observatories. We have developed the conceptual design for a RGS that meets the Constellation-X requirements and outlined a plan for demonstrating its technical readiness.

As a flagship mission, Constellation-X should be a general purpose facility for the astronomy community, not just a single purpose experiment for the study of black holes. As such, it needs to serve the AGN, WHIM and stellar astrophysics communities with adequate resolution to answer their questions. The reflection grating system that we described will enable Constellation-X to address the important questions of the next generation within the current $2Billion cost target. We believe Constellation-X needs to provide a significant increase in sensitivity and spectral resolution over previous missions in order to justify its cost and to live up to its potential. With a collecting area of ~10,000 cm^2 and a spectral resolution R~1500 to 3000 Constellation-X will advance X-ray astronomy to the next level of understanding of the composition and physical processes in the high energy universe.

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